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Optical scanning holography based on compressive sensing using a digital micro-mirror device

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ABSTRACT

Optical scanning holography (OSH) is a distinct digital holography technique, which uses a single two-dimensional (2D) scanning process to record the hologram of a three-dimensional (3D) object. Usually, these 2D scanning processes are in the form of mechanical scanning, and the quality of recorded hologram may be affected due to the limitation of mechanical scanning accuracy and unavoidable vibration of stepper motor's start-stop. In this paper, we propose a new framework, which replaces the 2D mechanical scanning mirrors with a Digital Micro-mirror Device (DMD) to modulate the scanning light field, and we call it OSH based on Compressive Sensing (CS) using a digital micro-mirror device (CS-OSH). CS-OSH can reconstruct the hologram of an object through the use of compressive sensing theory, and then restore the image of object itself. Numerical simulation results confirm this new type OSH can get a reconstructed image with favorable visual quality even under the condition of a low sample rate.

1. Introduction

Electronic acquisition of holographic signals from a physical object scene can be dated back to the pioneering work of Enloe et al. in the mid 1960s [1]. A Mach–Zehnder interferometer is employed to mix the reference laser beam and the object wave such that the interference pattern is recorded by a camera tube, i.e., a vidicon. Subsequently, the object scene can be reconstructed optically or digitally [1,2]. Numerous enhancements such as phase-shifting holography have been made based on this fundamental framework. Digital holograms are captured by a video camera and reconstructed by a computer with diffraction integral [3,4]. In this case focusing can be adjusted freely to yield images at arbitrary positions. However, the recording methods reported so far used an off-axis hologram that prohibits effective use of the pixel number of a CCD because of the necessity for carrier fringes [5]. The size of the reconstructed image is also limited by the presence of zero-order and conjugate images. An alternative solution was proposed, which was later known as optical scanning holography.

Optical scanning holography (OSH) is an unconventional form of electronic (or digital) holography. It can record the 2D holographic information of a 3D object in real time by a single raster scan [6]. The idea of OSH was first implicated by Poon and Korpel when they investigated bipolar incoherent image processing on their acousto-optic heterodyning image processor [7,8]. The method of holographic recording was further studied and demonstrated concretely by Duncan and Poon and they coined the technique as “optical scanning holography” to emphasize the fact that digital holographic recording is done by optical scanning - a novel departure from conventional digital holography [9]. Since then, OSH has undergone great development and has found various applications ranging from biological microscopy to remote sensing, pattern recognition and 3D cryptography etc [10,11]. Especially, OSH shows its broad prospects in the field of biomedical research because of quickly scanning and nondestructive testing for biological tissue. However, on the other hand, the lateral resolution of reconstructed images from OSH largely depends on the accuracy of 2D scan, and higher precision of 2D mechanical device will undoubtedly increase the system cost. Besides, mechanical scan is rely on the movement of stepper motor's start- stop, which will affect hologram recording due to its unavoidable slight vibration, thereby affecting the result of reconstructed image.

In this paper, we propose a new framework that replaces the 2D scanning devices with a Digital Micro-mirror Device (DMD). By control of micro rotation-mirrors on the DMD, the scanning light field can be modulated. And a single-pixel intensity sensor is employed to collect

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and response the modulated lights after they transmitted an object. Because DMD is used as the device to realize Compressive sensing (CS) process in this OSH framework, we call it OSH based on CS (CS-OSH). All micro mirrors on the DMD are controlled separately by computer according to a DMD configuration matrix, and for each configuration matrix, a value corresponding to the total intensity of modulated light field is recorded. In the process of CS-OSH, by changing DMD configuration matrix one after another, we can acquire a set of intensity values. And then, when the quantity of intensity values is enough, the hologram of object may be reconstructed with compressive sensing theory, and furthermore, we can restore the image of object from the hologram.

Compressive sensing [12–14] offers a method for simultaneous sensing and compression that relies on linear dimensionality reduction. The remarkable result of CS reveals that, with high probability, a sparse or compressible signal can be recovered from highly incomplete sets of linear measurements by a specially designed nonlinear recovery algorithm [15]. Typical application of CS is single-pixel camera, which captures the image of an object using only a single intensity detector [16]. This basic application creates a precedent of single-pixel imaging based on CS, but has its limitations: it can only record the intensity of the object. CS-OSH we proposed combines OSH technique with compressive sensing to realize the record of light wave in complex amplitude, which further expands the application range of CS from intensity recording to complex field recording, namely, we can get not only the intensity distribution of an object, but also its phase distribution.

The organization of the paper is given as follows. Following the introduction, our proposed method is reported in Section 2, where we describe the principles of operation of OSH technology, and how our proposed method can be incorporated into the framework. Numerical simulation and analysis will be presented in Section 3. Finally, a conclusion of the paper will be given in Section 4.

2. Proposed CS-OSH

2.1. Overall View of OSH and CS-OSH Systems

As described in previous literatures [6–8], OSH is a technique whereby a 3D object scene is scanned by a time-varying Fresnel Zone Plate (FZP), and the diffracted wave at each instance of the scanning is recorded with a single pixel sensor such as a photodetector.

Both schematics of OSH and CS-OSH are shown in Fig. 1. The laser source emits a beam of light with temporal frequencies of ω, and split into two by the beamspliter BS1. One of the beam's temporal frequency is shifted to $\omega + \Omega$ by an acousto-optic frequency shifter (AOFS).

For OSH, the transmitted and reflected beams from BS1 pass through the pupils $p_1(x, y)$ and $p_2(x, y)$, and then combined by BS2 to eventually project the interference of the plane and spherical waves, which has become a time-varying FZP, on the object. The scanning process can be done by mounting the object on an X–Y motorized scanner, as shown in the Fig. 1(a). The output from the detector is a sequence of hologram pixels, each corresponding to a unique point on the hologram plane.

For CS-OSH, instead of mechanical scanning device, we use a digital micro mirror device to code the holography information by changing the DMD matrix, as shown in Fig. 1(b). Before the two split beams combined together, one of them is projected on the DMD. The DMD configuration matrix is denoted as $m(x, y)$, which means the distribution of the light passing through DMD is modulated as configuration matrix. Then, the combined optical beams illuminate an object with transmittance distribution $\gamma(x, y, z)$, which is located at a distance of z away from the DMD. The transmitted light with object information is recorded by a photoelectric detector (PD) and converted to an electrical signal $i(t)$.

To every change of DMD configuration matrix, the photoelectric detector gives an electrical signal corresponding to the total light intensity at that moment. Of course, the current $i(t)$ consists of a direct current and a heterodyne alternating current $i_\Omega(t)$ at frequency of Ω. Then a heterodyne detection is implemented: passing through a band pass filter (BPF) with the center frequency of Ω , $i_\Omega(t)$ is divided into two parts, and they are multiply with signals of $\cos(\Omega t)$ and $\sin(\Omega t)$ respectively, and next, inphase component i_c and quadrature components i_s are extracted from the heterodyne alternating current $i_\Omega(t)$ by low pass filters (LPF), and ultimately stored in a computer after converted into digital form.

Similar as OSH, the whole process of CS-OSH can be divided into two stages, i.e., coding and decoding stages, and the goal of both stages is to get the holograms of an object or a pinhole [6]. In CS-OSH, however, we cannot get the holograms directly just like that in OSH. To achieve the goal, each stage consists of two key steps, the first is for data-recording, as described above, we can get M pairs of data by changing the DMD configuration matrix M times; and the second is for hologram-reconstructing, the hologram of object (or pinhole) can be reconstructed by CS optimization algorithms from the M pairs of digital data.

2.2. Theoretical background of CS-OSH

In the data-recording step, suppose the light beam in Fig. 1(b) is a plane wave with temporal frequency $\omega + \Omega$. Its complex field just before the object can be written easily as $\exp[j(\omega + \Omega)t]$. For the other beam with temporal frequency ω, its complex field $w(x, y; z)$ in front of the object can be expressed as $w(x, y; z) = m(x, y)*h(x, y; z)$ by using the Fresnel diffraction formula, where * represents the convolution and $h(x, y; z)$ is the point spread function of Fresnel diffraction. So the total complex field $T(x, y; z)$ projected on the object, can be obtained by means of adding the two lights with different temporal frequencies, that is $T(x, y; z) = \exp[j(\omega + \Omega)t] + w(x, y, z)\exp(j\omega t)$. Following the step of signal transmission, the expression of processed current $i_\Omega(t)$ by BPF can be deduced.

$$
\begin{aligned}
i_\Omega &= \mathrm{Re}\left[\iint_D w(x, y; z)|\gamma(x, y, z)|^2 dxdy \exp(j\Omega t)\right] \\
&= |i_{\Omega_p}|\cos(\Omega t + \phi_p)
\end{aligned} \tag{1}
$$

where,

$$
\begin{aligned}
i_{\Omega_p} &= \iint_D w(x, y; z)|\gamma(x, y, z)|^2\, dxdy \\
&= |i_{\Omega_p}|\exp(j\phi_p)
\end{aligned} \tag{2}
$$

And Re [] is the real part of the content inside the bracket; D is the pupil size; $\gamma(x, y, z)$ represents the transmittance distribution of object. $|i_{\Omega_p}|$ and ϕ_p denote the amplitude and phase parts of i_{Ω_p}, respectively.

Then, the heterodyne current splits into two channels and goes through the lock-in detection to give two quadrature outputs, $i_s = |i_{\Omega_p}|\sin(\phi_p)$ and $i_c = |i_{\Omega_p}|\cos(\phi_p)$, which are the real and imaginary parts of Eq. (2). Note that a pair of digital values can be obtained after two quadrature outputs passing through AD convertors, and in fact they form a complex signal finally stored in the computer in Fig. 1(b).

This expression of signal can be discretized as

$$
\begin{aligned}
i_{\Omega_p} &= \iint_D [m(x, y)*h(x, y, z)]|\gamma(x, y, z)|^2 dxdy \\
&= \iint_D [|\gamma(x, y, z)|^2 * h(x, y, z)]m(x, y)dxdy \\
&\propto \sum_{j=1}^{n}\sum_{i=1}^{n} m(x_i, y_j)l(x_i, y_j; z)
\end{aligned} \tag{3}
$$

where x_i, y_j represent the discretization of coordinates x, y; n is the sample number; hologram $l(x_i, y_j; z)$, which can be represented by Eq. (4), actually performs Fresnel diffraction of the object, and the Parseval's formula is used during the deducing of Eq. (3).

$$
l(x_i, y_j; z) = |\gamma(x_i, y_j, z)|^2 * h(x_i, y_j, z) \tag{4}
$$